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_ NEWS

Multiband OFDM: Why it Wins for UWB

With FCC rulings in place, the stage is set for UWB to take off in the sector. By turning to multi-band OFDM architectures, designers can gain the flexibility, power consumption and costs needed to make UWB come to life.

By Anuj Batra, Jaiganesh Balakrishnan, and Anand Dabak, Texas Instrument

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Over the last year and half, ultra-wideband (UWB) communication systems have received significant attention from industry, media and academia. The reason for all this excitement is that this technology promises to deliver data rates that can scale from 110 Mbit/s at a distance of 10 meters up to 480 Mbit/s at a distance of two meters in realistic multi-path environments all while consuming very little power and silicon area. It is expected that UWB devices will provide low cost solutions that can satisfy the consumer's insatiable appetite for data rates as well as enable new consumer market segments.

But for UWB systems to move from the lab environment to real-life system designs, engineers must battle traditional design issues such as complexity, power consumption, cost, and flexibility. Fortunately, an answer to these problems has arrived. By turning to a multiband OFDM approach, designers can overcome many of these barriers. Lets see how.

The FCC Helps Out
Much of the increased attention on UWB technology is due to the landmark ruling by the Federal Communications Commission (FCC). In February 2002, the FCC opened up 7,500 MHz of spectrum (from 3.1 GHz to 10.6 GHz) for use by UWB devices. This ruling has generated considerable interest in developing UWB communication systems, primarily through standards effort: such as IEEE's 802.15.3a, and has created several new opportunities for innovation and technical advancement.

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Even though the FCC has allocated the entire spectrum from 3.1 GHz and 10.6 GHz for UWB, it has been shown that using an upper frequency beyond 4.8 GHz leads to an improvement in the overall link margin of only 1 dB with current RF CMOS technology. This comes at the expense of higher complexity, and higher power consumption.

The minimal gains in the link budget and the increase in complexity and power consumption lead one to conclude that the bandwidth between 3.1 an 4.8 GHz will provide the most effective bandwidth for initial deployments of UWB devices. Indeed, limiting the upper frequency to 4.8 GHz also has several decided advantages, including shortening time to market, simplifying the design of the RF and analog front-end circuits (low noise amplifiers and mixers), making it more amenable to CMOS technology, and avoiding interference from the U-NII band, where IEEE 802.11a signals reside.

Of course, limiting the bandwidth of UWB, at least initially, still leaves the possibility that the entire bandwidth will eventually be utilized. As RF technology improves, it will become more efficient to use the upper frequencies in the UWB range. If defined with forethought and proper planning, the UWB systems can accommodate an effective migration path to the upper end of the spectrum when market conditions dictate such a move.

System Design Issues
Given the bandwidth from 3.1 to 4.8 GHz, there are several ways to design a UWB communication system. One method is to use the entire 1700 MHz of bandwidth and spread the transmitted information using spread spectrum or code-division multiple access (CDMA) techniques.

The main advantage of building UWB communication systems based on spread-spectrum techniques are that these techniques are well understood and have been proven in other commercial technologies (ex. wideband CDMA). However, building RF and analog circuits as well as high speed analog-to-digital converters (ADCs) to process this extremely wideband sign, is a challenging problem. In addition, the digital complexity needs to be quite large (at least 16 RAKE fingers) in order to capture sufficient multi-path energy to meet the range requirements of 10 meters for a 110 Mb/s system.

In addition to allocating spectrum, the FCC also specified that a UWB signal must occupy a minimum 10-dB bandwidth of 500 MHz. In many ways, this portion of the ruling has revolutionized the design of UWB communication systems. Instead of having to use the entire band to transmit information, the spectrum can now be divided into several sub-bands, whose bandwidth i approximately 500 MHz. By interleaving the symbols across sub-bands, UWB systems can still maintain the same transmit power as if they were using the entire bandwidth.

The advantage is that the information can now be processed over a much smaller bandwidth, thereby reducing the complexity of the design, reducing the power consumption, lowering the cost, and improving spectral flexibility and worldwide compliance. Other advantages of this approach include using lower-rate ADCs and simplifying the digital complexity. Systems built using this type of approach are often referred to as multiband systems.

Understanding the Multiband Approach
For a multiband system, information on each of the sub-bands can be

transmitted using either single-carrier (pulse-based) or multi-carrier (OFDM) techniques.

Single-carrier multiband systems transmit information by modulating the phase of a very narrow pulse. The main advantage of this type of system is that the transmitter has a very simple design. Some disadvantages are that is difficult to collect significant multi-path energy using a single RF chain; switching time requirements can be very stringent (less than 100 ps) at both the transmitter and receiver; the receiver signal processing is very sensitive to group delay variations introduced by analog front-end components; and spectral resources are potentially wasted in order to avoid narrowband interference.

Multi-path energy collection is also a fundamental issue because it determine the range of a communication system. It has been shown that with a single RF receive chain, the pulse-based system cannot achieve the required 10-m range. However, it is possible to finally achieve the necessary range with the multi-band approach, but it usually comes at the expense of increases in receiver complexity (i.e. multiple RF receive chains), power consumption, analog die size and increased design time.

On the other hand, multi-carrier, multi-band systems use orthogonal frequency division multiplexing (OFDM) techniques to transmit the information on each of the sub-bands. OFDM has several nice properties, including high spectral efficiency, inherent resilience to RF interference, robustness to multi-path, and the ability to efficiently capture multi-path energy. It is also well understood and has been proven in other commercial technologies (ex. IEEE 802.11a/g).

The main advantages are that it is easier to collect multi-path energy using a single RF chain, relaxed switching times, insensitivity to group delay variations, and ability to deal with narrowband interference at the receiver without having to sacrifice sub-bands or data rate. The only drawback of this type of system is that the transmitter is slightly more complex because it requires an IFFT and the peak-to-average ratio may be slightly higher than that of the pulse-based multi-band approaches.

Diving into Multiband OFDM
Now that we've taken a brief look at the different multi-band approaches available to designers, let's examine the OFDM-based multiband approach further.

Given the frequency band from 3.1 GHz to 4.8 GHz and the FCC requirement that UWB signals have to be at least 500 MHz, only three sub-bands can be used in the initial deployment of multi-band OFDM systems. **Figure 1** illustrates one way to allocate the three sub-bands with the given frequency allocation.
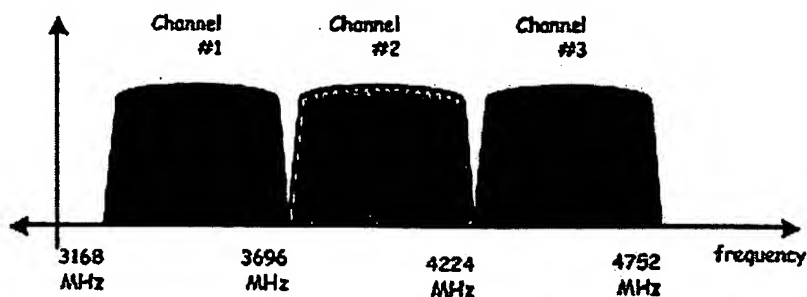
Figure 1: Frequency allocation of sub-bands for a multi-band OFDM system.

The frequency planning shown in Figure 1 was chosen for two reasons. First allows sufficient guard band on the lower side of channel number 1 and the upper side of channel number 3 to simplify the pre-select filter's design. Second it ensures that both the transmitter and receive can switch to the next center frequency within a few nanoseconds.

Figure 2 provides an example of how the OFDM symbols are transmitted in multi-band OFDM system. This figure shows that the first OFDM symbol is transmitted on channel number 1, the second OFDM symbol is transmitted o channel number 3, the third OFDM symbol is transmitted on channel number 2, the fourth OFDM symbol is transmitted on channel number 1, and so on.
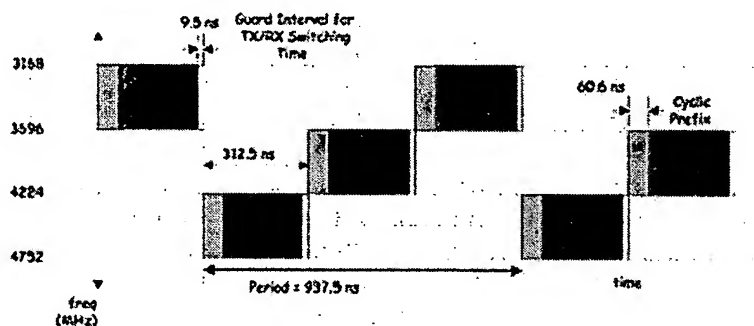

Figure 2: An example of time-frequency interleaving for the multi-band OFDi system.

In Figure 2, it is assumed that time-frequency interleaving (TFI) is performe across just three OFDM symbols. In practice, the TFI period can be much longer. The exact length and pattern of the TFI may differ from superframe t superframe and piconet to piconet.

From Figure 2, it is also apparent that a cyclic prefix (CP) is inserted at the beginning of each OFDM symbol and a guard interval (9.5 ns) is appended tc each OFDM symbol. The guard interval has been inserted to ensure that only a single RF transmit and RF receiver chain are needed for all channel environments and all data rates and that there is sufficient time for the transmitter and receiver to switch to the next channel.

Figure 3 is an example of a block diagram for a transmit architecture implementing the multi-band OFDM system. The transmitter's structure is very similar to that of a conventional wireless OFDM physical layer, except that the carrier frequency is changed based on the time-frequency

interleaving pattern. Other modifications have also been made to reduce complexity.
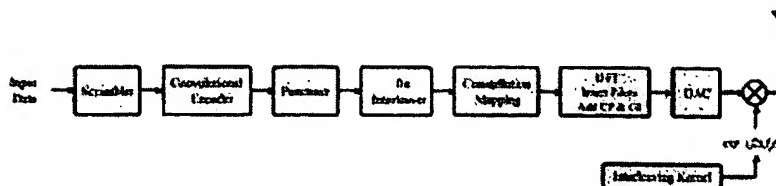

Figure 3: Example transmitter architecture for a multi-band OFDM system.

Multi-Path Robustness

An OFDM system offers inherent robustness to multi-path dispersion with a low-complexity receiver. Adding a CP forces the linear convolution with the channel impulse response to resemble a circular convolution. A circular convolution in the time domain is equivalent to a multiplication operation in the discrete Fourier transform (DFT) domain. Hence, a one-tap frequency domain equalizer is sufficient to undo the effect of the multi-path channel.

The length of the CP determines the amount of captured multi-path energy. Any multi-path energy outside the CP window would result in inter-carrier-interference (ICI). The CP length should be chosen to minimize the performance degradation due to the loss in collected multi-path energy and the resulting ICI, while still keeping the CP overhead small.

The UWB channel models are highly dispersive. The worst-case channel environment is expected to have a root-mean-square (rms) delay spread of 25 ns. **Figure 4** illustrates the CP length's impact for the 4 to 10 m, non-line of-sight (NLOS) channel environment.
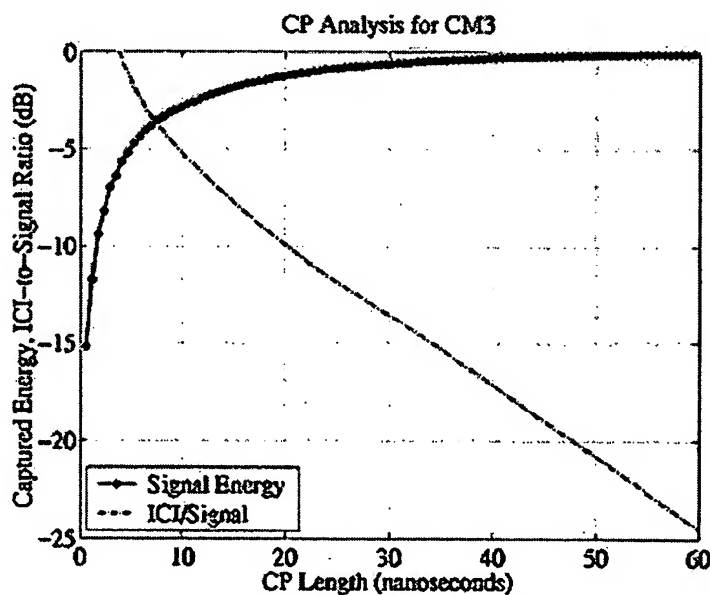

Figure 4: Captured multi-path energy as a function of CP length for a 4 to 1(m, NLOS channel environment.

In Figure 4, the ICI-to-signal ratio is shown at the decoder's input and it

incorporates the processing gain for 110 Mbit/s. To sufficiently capture the multi-path energy and minimize the impact of ICI/ISI for all channel environments, the CP duration was chosen to be 60.6 ns.

Tone Allocation

Increasing the number of tones in an OFDM system decreases the overhead due to CP. On the other hand, the complexity of the Fast Fourier transform/inverse Fast Fourier transform (FFT/IFFT) block increases and the spacing between adjacent tones decreases.

To provide the best tradeoff between the CP overhead and FFT complexity, the multiband OFDM system uses 128 tones. To be compliant with FCC regulation, the 10-dB bandwidth of an UWB signal ought to be at least 500 MHz. This implies the use of at least 122 tones. Hence, the 128 tones are partitioned into 100 data tones, 22 pilot tones and 6 null tones.

Among the 22 pilot tones, 12 would be standard-defined pilot tones and 10 would be user-defined pilot tones. The 12 standard-defined pilot tones are sufficient to estimate/track phase variations due to carrier/timing frequency mismatch. To relax the specifications on the channel select filter, the tones a the edge of the spectrum are either null tones or user-defined pilot tones.

PAPR: A Critical Parameter

The peak-to-average power ratio (PAPR) requirement of an OFDM system is critical parameter in assessing whether the system can be implemented in CMOS. A large PAPR requirement dictates higher peak transmit power for the transmit DAC. Allowing a small percentage of clipping at the DAC can decrease the PAPR.

For an OFDM multiband UWB system, restricting the PAPR to 9 dB results in performance degradation of less than 0.1 dB. In addition, as the FCC has limited the transmit power of UWB systems to -41.25 dBm/MHz, the average transmit power of a multi-band OFDM system is -9.5 dBm. A PAPR of 9 dB results in a peak transmit power of less than 0 dBm, which is realizable in CMOS technology without the need for an external power amplifier.

Spectral Flexibility

The unlicensed nature of the UWB spectrum makes it essential for a UWB device to coexist with other devices that share the same spectrum. In addition, the UWB spectral allocation could potentially be different in differer regions of the world. For example, the Japanese government has encourager wireless system developers to avoid several narrow bands within the UWB spectrum that have been allocated for radio astronomy.

Multiband OFDM can comply with local regulations by dynamically turning off certain tones or channels in software. This capability will help with the worldwide adoption of multi-band OFDM systems.

The flexibility and dynamic nature of a multi-band OFDM system allows it to coexist effectively with a wide range of current and future wireless technologies. A primary advantage of OFDM is its robustness to narrow-band interferers.

Since the tone spacing is 4.125 MHz, the resolution of the multi-band OFDM

system is much narrower than the band resolution of 500 MHz for pulse-based multi-band systems. Any narrow band interference will at most affect couple of OFDM tones. The information in these tones can be recovered through the forward error correction codes.

Complexity/Power Consumption
Some may perceive OFDM as a complex modulation technique, but the multiband OFDM system has been specifically designed to be a low complexity solution. By limiting the transmitted symbols to a quadrature phase-shift keying (QPSK) constellation, the resolution of the DAC/ADC and the internal precision in the digital baseband, especially the FFT, can be lowered. Simulations indicate that 4-bit quantization at the receiver has less than 0.1 dB of degradation for typical data rates.

This system's lower complexity is also due to the relatively large spacing between the carriers when compared to an IEEE 802.11a system. This large spacing relaxes the phase noise requirements on the carrier synthesis circuitry and improves robustness to synchronization errors.

Multiband OFDM has decided advantages over other possible implementatior of UWB in terms of the simplicity as well as the efficiency of its multi-path energy capture. For a clock speed of 102.4 MHz, a 128-point IFFT/FFT, required for multi-band OFDM, performs 10 complex multiplications every clock cycle. This complexity is equivalent to that of a complex 4-tap RAKE receiver, for a single-carrier multi-band implementation, running at 256 MHz

The multiband OFDM system has been specifically designed for a single analog receiver chain. This simplifies the overall architecture considerably; shortening the time to market by allowing the use of currently available and market-tested RF design techniques and components. The estimated power consumption of a multi-band OFDM implementation in 90 nm CMOS technology node is tabulated in **Table 1**.

Table 1: Estimated power consumption for the multi-band OFDM system in a 90 nm CMOS process

	93 mW	155 mW	15 µW
	93 mW	169 mW	15 µW

System Performance
The performance of a multi-band OFDM system was evaluated based on simulations for various data rates and channel environments. The simulation incorporate losses due to clipping at the DAC, ADC degradation, packet acquisition, channel estimation, clock frequency mismatch, carrier recovery/tracking, etc. **Table 2** shows the range at which the system can achieve a 90 percent link success probability for an eight percent target packet-error-rate. These results demonstrate that the system can achieve a distance of 11 m for 110 Mbit/s.

Table 2: Ninety percent link success probability distance for a multi-band OFDM system as a function of data rate and channel environment.

	20.5 m	11.5 m	10.9 m	11.6 m	11.0 m
	14.1 m	6.9 m	6.3 m	6.8 m	5.0 m
	7.8 m	2.9 m	2.6 m	—	—

Wrap Up

The multi-band OFDM system described in this article provides details about the fully compliant implementation of a UWB communication system based c CMOS technology featuring low power, low complexity, low cost and the ability to communicate at rates in excess of 110 Mbit/s over distances beyon 10 meters, depending on the data rate and the channel conditions. In addition, systems based on multi-band OFDM have a high degree of flexibilit so they can co-exist effectively with existing wireless technologies and adapt to the various regulatory requirements in different regions of the world.

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